Detrital chromian spinels in Devonian-Carboniferous sandstones of Hikoroichi area,NE Japan : their provenance and tectonic relationship

著者	Hisada Kenichiro, Bunyoungkul Thitikorn, Charusiri Punya
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Detrital chromian spinels in Devonian-Carboniferous sandstones of Hikoroichi area, NE Japan: their provenance and tectonic relationship

Ken-ichiro Hisada, Thitikorn Bunyoungkul* and Punya Charusiri**

Abstract

A total of 30 sandstones were collected from the well-defined mappable units of Middle Devonian to Early Carboniferous ages in the South Kitakami Terrane (= SKT), NE Japan. They are classified as litharenite, feldspathic litharenite, and lithic arkose. QFL discrimination diagram of the studied sandstones indicates the provenance of magmatic arcs. Detrital chromian spinels, present as accessory minerals in the rocks, are discovered from 6 clastic samples. A total of 37 detrital chromian spinels are determined for their major-oxide analysis using EPMA. Fe-Cr-Al diagram displays rather low Fe^{3+} values, suggesting the provenance from ultramafic regions. The result also indicates that most chromian spinels have wider ranges of Cr/(Cr+Al). The rather low values of TiO_2 contents suggest that the sandstone-hosted spinels were derived from ultramafic provenance. These lines of evidence support the idea that spinel-bearing sandstones were derived from ultramafic sources occurring in the fore-arc tectonic setting of the northern peri-Gondwana Land.

Key words: Detrital chromian spinels, sandstone, Devonian-Carboniferous, serpentinite, South Kitakami Terrane

Introduction

Chromian spinel [(Fe, Mg)(Cr, Fe, Al)$_2$O$_4$], the solid-solution mineral in a spinel group, is an accessory mineral found only about 1 or 2 % in mafic and ultramafic rocks. From the wide compositional range of chromian spinel in both divalent (Mg^{2+} and Fe^{2+}) and trivalent (Al^{3+}, Cr^{3+}, and Fe^{3+}) elements, it is known that this mineral must be relatively sensitive to the chemical and thermal conditions. Thus, its chemical compositions can be potentially used as extremely important indicators of host rock tectonic settings or of physico-chemical conditions under which its host rock had been formed (Irvine, 1965; Dick and Bullen, 1984; Press, 1986; Pober and Faupl, 1988; Arai, 1990).

Although chromian spinel, in nature, occurs as an accessory mineral, it is chemically more durable than other mafic minerals, and unaltered simply by serpentinization. Moreover, lack of cleavage and high degree of hardness offer the further advantages of mechanical stability. Thus, chromian spinel still remains after the long processes of weathering, erosion, and transportation. Through these processes, this mineral can be found again in the form of detrital chromian spinel in the clastic sedimentary rocks, especially in sandstones and siltstones.

The worldwide occurrence of detrital chromian spinels has been encountered by many geologists as demonstrated and summarized by Zimmerle (1984). He also mentioned that the distribution patterns of those detrital chromian spinels often show their sources on the continents, mostly in ophiolite belts, as well as in the deep-sea, in subduction zones or mid-ocean ridges.

Japan is one of countries where detrital chromian spinels occur from the Paleozoic and Mesozoic clastic sedimentary rocks throughout

* Unocal Thailand, Ltd., Chatuchak, Bangkok 10900, Thailand

** Department of Geology, Faculty of Science, Chulalongkorn University, Bangkok 10330, Thailand

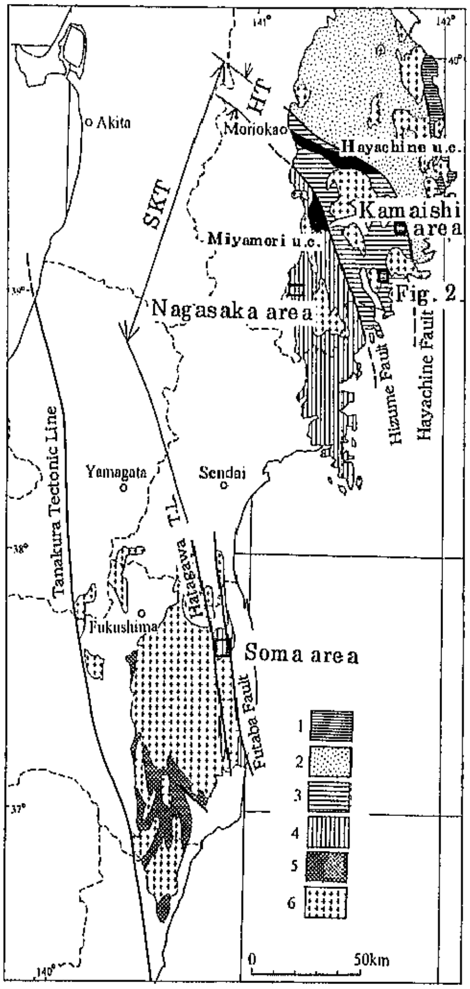

Fig. 1. Tectonic map of basement complex of Northeast Japan (modified from Umemura and Hara, 1985). 1: Taro belt, 2: North Kitakami belt, 3: South Kitakami belt, 4: Matsugadaira-Motai belt, 5: Abukuma belt, 6: Cretaceous granite. SKT: South Kitakami Terrane, HT: Hayachine tectonic belt, u.c.: ultramafic complex.

it (e.g., Arai and Okada, 1991; Hisada and Arai, 1993; Nanayama *et al.*, 1993; Hisada *et al.*, 1994; Takeuchi, 1994; Hisada *et al.*, 1995; Yoshida *et al.*, 1995; Hisada *et al.*, 1996; Kadoshima and Arai, 1999). Chemistry of these detrital chromian spinels has been used as a tool to unravel the tectonic settings of their provenances effectively.

In the South Kitakami Terrane (= SKT) (Fig.1), nearly complete sequences of the Paleozoic and Mesozoic strata ranging from Silurian to earliest Cretaceous are observed. Some detrital chromian spinels had already reported in Silurian (Yoshida *et al.*, 1995), Devonian to Carboniferous (Hisada *et al.*, 1995, 1997; Hisada and Arai, 1999), and Jurassic (Takeuchi, 1994) beds within this terrane. However, no detrital chromian spinel has been found yet from the Hikoroichi area, one of the famous type localities of Devonian to Carboniferous. In this study, detrital chromian spinels were detected from Devonian to Carboniferous sandstones and siltstones of the Hikoroichi area. This new discovery of detrital chromian spinels from these rocks gives the important clue to interpret tectonic setting of the South Kitakami Terrane more clearly.

General geology of South Kitakami Terrane

SKT is composed largely of shallow marine strata ranging in age from Paleozoic to Mesozoic. These strata are underlain by pre-Silurian igneous and metamorphic basement complexes (Umemura and Hara, 1985; Kawamura, M. *et al.*, 1990; Ehiro and Kanisawa, 1999). The basement rocks mostly exist within and along two major tectonic lines, namely Hayachine and Hizume Faults in the Southern Kitakami Mountains (Fig.1). The basement rocks also occur narrowly between the Hatagawa Tectonic Line and Futaba Fault in the easternmost part of the Abukuma Mountains (Fig.1). The basement complexes comprise mainly Matsugadaira-Motai metamorphic rocks, Hikami granites and Hayachine-Miyamori ultramafic complex. The study area, the Hikoroichi area, is located between the Hayachine and Hizume Faults in the northeastern portion (= Hayachine tectonic belt) of SKT (Fig.1). The stratigraphic outline of the Hayachine tectonic belt is briefly presented herein (Table 1).

The Matsugaira-Motai metamorphic rocks of high P/T type invariably contain alkali amphibole and pumpellyite, and are composed mainly of greenschist, pelitic schist, amphibolite, serpentinite, and subordinate psamitic and siliceous schist. They are interpreted as mixtures of

Table 1. Stratigraphic correlation of the Paleozoic in the Abukuma and Southern Kitakami Mountains. (after Ehiro and Kanisawa, 1999)

		Soma Hisada et al. (1995)	Nagasaka Hisada et al. (1997)	Hikoroichi This study	Kamaishi Hisada and Arai (1999)
Carboniferous	L	Tateishi Fm.	Takezawa Fm.	Nagaiwa Fm.	
				Onimaru Fm.	Kogawa Fm
	E	Mano Fm.	Karaumedate Fm.	Hikoroichi Fm.	
Devonian	L	Ainosawa Fm.	Tobigamori Fm.		
	M ~ E			Nakazato Fm.	Sonjyogataki Fm. Sunagohata M. Osawagawa M.
				Ono Fm.	
Silurian				Kawauchi Fm.	Hayachine ultramafic complex
				Hikami Granites	
Ordovician ~ Cambrian			Matsugadaira Met. Rocks - Motai Met. Rocks		

continental and oceanic crustal rocks (Maekawa, 1981). The Hayachine-Miyamori ultramafic complex, or the so-called Hayachine Complex by Ehiro *et al.* (1988), is characterized by the abundance of mafic to ultramafic rocks in the lower, dolerite and basalt in the middle and shale/sandstone and siliceous rocks in the upper sequences. Gabbro and hornblendite of the complex yield an average K-Ar age of 452 $\pm$ 18.5 Ma (Shibata and Ozawa, 1992). The Hikami granites and associated Shoboji diorites/gabbros were also dated as the nearly same and/or slightly younger ages using SHRIMP U-Pb zircon (Ehiro *et al.*, 1995).

Unmetamorphosed Middle Paleozoic strata unconformably overlie these basement complexes. The followings are the brief explanation of the stratigraphy based on Onuki (1969), Kawamura, M. (1983), Kawamura, T. (1983) Oide *et al.* (1989) and Mori *et al.* (1992). The oldest rock sequences include Early Silurian pyroclastic rocks in the Hayachine tectonic belt, where the 90 m-thick Okuhinotsuchi Formation consists of terrestrial mudstone, felsic welded tuff, sandstone and impure limestone in the lower member and bedded limestone, welded tuff and tuffaceous sandstone in the upper member. The slightly younger, 100-m thick, Kawauchi Formation in the Hikoroichi area (Table 1) comprises basal conglomeratic sandstone and overlying limestone with intercalated mudstone. Both formations contain the outstanding coral fossils, *Halysites* sp. and *Favosites* sp., as well as brachiopods, trilobites, bryozoas, and algaes.

Conformably overlying the Silurian strata are the 500 m-thick sequences of the Ono Formation of Devonian age in the Hikoroichi area (Table 1). The sequences are composed largely of three members including purple red to dark green mudstone in the lower, coral-bearing limestone with volcanic tuff in the middle, and volcanic tuff, sandstone/mudstone, and coral-rich limestone in the upper. The Ono Formation is overlain by the 500-m thick Nakazato Formation of Middle Devonian. The Nakazato Formation comprises mainly mafic tuff with subordinate

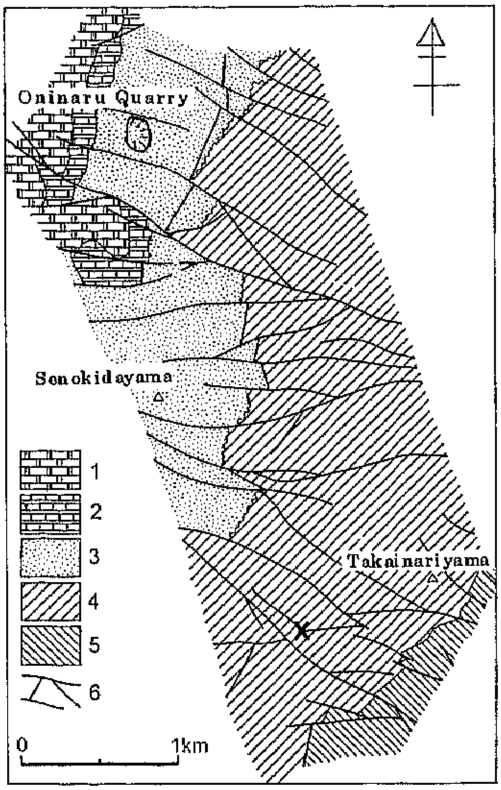

Fig. 2. Geologic map of the Hikoroichi area (simplified from Kawamura, T. in Oide *et al.* (eds.), 1989). 1: Nagaiwa Fm., 2: Onimaru Fm., 3: Hikoroichi Fm., 4: Nakazato Fm., 5: Ono Fm., 6: faults. X: Locality for detrital chromian spinels from the Nakazato Fm. The Hikoroichi Fm at the Onimaru quarry yields the detrital chromian spinels.

mudstone in the lower member, interbedded black mudstone and felsic tuff in the middle member, and alternating sandstone with felsic tuff in the upper member (N1 to N4 Members).

Unconformably overlying the Devonian strata are Lower Carboniferous strata of the Hikoroichi Formation (500 to 1,700 m-thick) in the Hikoroichi area (Table 1). The Hikoroichi Formation is marked at the bottom by basal conglomerates. This formation (H1 to H4 Members) and the overlying conformable formations comprise shale with sandstone intercalation. The Hikoroichi Formation is conformably overlain by the 75 m-thick, coral-rich Onimaru Formation. In the Hikoroichi area, Upper Carboniferous carbonate sequences of the Nagaiwa

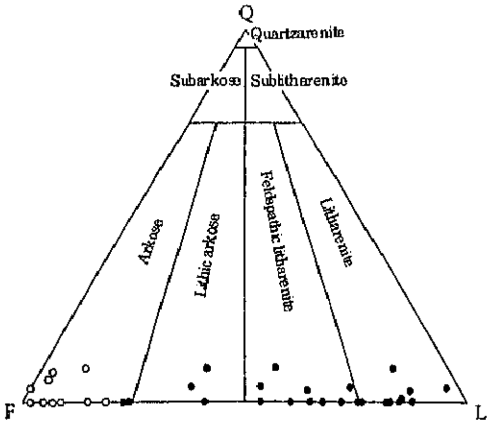

Fig. 3. QFL plots (Folk, 1968) of sandstones from the Hikoroichi Formation. Open circles: Permian to Cretaceous sandstones from the Southern Kitakami Mountains (our unpublished data), closed circles: Carboniferous sandstones form the Hikoroichi Fm.

Formation conformably overlie those of the Onimaru Formation with paraconformity.

Occurrences of chromian spinels

Thirty samples of clastic rocks of Devonian and Carboniferous ages obtained from the Hikoroichi area (Fig. 2) were petrographically studied for mesoscopic and microscopic investigations.

Among the samples collected, six specimens of sandstones were obtained from the Nakazato Formation along the Omorizawa ravine in the Hikoroichi area. Thin sections from these samples were prepared for more detailed petrographic description. Twenty grains of chromian spinels were observed in one thin section out of six ones.

Lithology of chromian spinel-bearing sandstone collected from the uppermost part of the N2 Member (X in Fig. 2) is fine- to medium-grained. Greenish to lightly grey colours and rather ill sorting are quite diagnostic features of this sandstone. Petrographically the Devonian sandstones comprise abundantly angular rock fragments and feldspar minerals. Essential rock fragments up to gravel sizes exhibit rather mafic volcanic constituent. Feldspar grains are usually subangular to subrounded, mostly prismatic and short tabular Ca-rich plagioclase. Some carbonates normally occur as precipitated cementing materials. The rocks in general display mineralogical and textural immaturity.

Seventeen samples of Lower Carboniferous sandstones were obtained from the H2 to H4 Members of the Hikoroichi Formation at the Onimaru quarry (Fig. 2) and prepared for petrographic examination. Among these samples, 20 grains of detrital chromian spinels were detected from five thin sections of H2 Member.

The examined sandstones of the Hikoroichi Formation are mostly litharenite and feldspathic litharenite which are characterized by high contents of rock fragments (up to 75%) with subordinate feldspar clasts (up to 25%) (Fig. 3). Quartz grains, on the other hand, are rarely observed, mostly less than 10% of the rock. Rock fragments are mostly of volcanic origin. Crinoid-bearing carbonate clasts are also observed in some thin sections. Calcic plagioclase fragments and mica flakes, though not abundant, are commonly found as matrix in the studied sandstones. Ill sorting as well as low sphericity and roundness support textural immaturity of the rocks. The high abundance of volcanic fragments and low contents of quartz clasts give rise to the low mineralogical maturity.

Under the microscope, detrital chromian spinels from the Nakazato Formation are characterized by high-relief, reddish to yellowish brown and almost isotropic grains (Fig. 4). Their sizes vary considerably from 10 to 340 microns. Some of the spinels display subhedral crystals with octahedral habits.

The chromian spinels from the Hikoroichi Formation exhibit similar physical appearance (Fig. 5). High-relief, isotropic and reddish to dark brown colours are very characteristic. However only a few grains are yellowish brown. Spinels of Carboniferous sandstones are relatively smaller than those of the Devonian ones, usually ranging from 10 to 90 microns. Relict octahedral crystal forms are well recognized in several angular grains (Fig. 5).

Table 2. Representative microprobe analyses of detrital chromian spinels from the Nakazato Formation.

	D3	D5	D9	D13	D16
SiO_2	0.07	0.024	0.05	0.05	0.04
Al_2O_3	7.92	33.57	15.70	12.29	17.87
TiO_2	0.25	0.055	0.04	0.16	0.61
Cr_2O_3	59.00	35.568	54.49	53.81	49.09
FeO*	21.90	16.045	18.18	23.33	20.63
NiO	0.0	0.067	0.02	0.02	0.08
MnO	0.34	0.182	0.45	0.36	0.25
MgO	10.48	15.473	11.34	9.26	11.66
CaO	0.01	0.018	0.03	0.00	0.04
Na_2O	0.00	0.046	0.00	0.01	0.01
K_2O	0.02	0.05	0.01	0.00	0.03
Total	100.02	101.099	100.30	99.29	100.30
Mg#	0.52	0.66	0.54	0.46	0.56
Cr#	0.83	0.42	0.70	0.75	0.65
Cr3#	0.78	0.40	0.69	0.71	0.62
Al3#	0.16	0.57	0.29	0.24	0.34
Fe3#	0.06	0.03	0.02	0.05	0.04

FeO*: total iron as FeO. Mg#: Mg/(Mg + Fe^{2+}) atomic ratio. Cr#: Cr/(Cr+Al) atomic ratio. Cr3#:, Al3#: and Fe3#: atomic fraction of Cr, Al and Fe^{3+}, respectively, for trivalent cations (Cr + Al + Fe^{3+}). Ratios of Fe^{2+} and Fe^{3+} were calculated assuming spinel stoichiometry.

Chromian spinel geochemistry

Chromian spinels from Devonian to Carboniferous sandstones of the Hikoroichi area were analyzed by a microprobe (JEOL JXA-862) at the Chemical Analysis Center, the University of Tsukuba. Cation fractions of Mg, Fe^{2+}, Al, Cr and Fe^{3+} were calculated assuming spinel stoichiometry after allotting of Ti to ulvöspinel molecule. Selected analyses of the detrital chromian spinels are listed in Tables 2 and 3.

From the geochemical results of the detrital chromian spinels of the Nakazato Formation (Table 2), it is clear that Cr_2O_3 (up to 59%) is the major composition of the mineral with the average of about 44.4%. Al_2O_3 of these chromian spinels is always low in comparison with those of Cr_2O_3. The negative correlation between Al_2O_3 and Cr_2O_3 may indicate the substitution of Cr^{3+} by Al^{3+} under lowering temperatures (cf., Arai and Okada, 1991). Some chromian spinel grains where Cr^{3+} was substituted by Al^{3+} al-

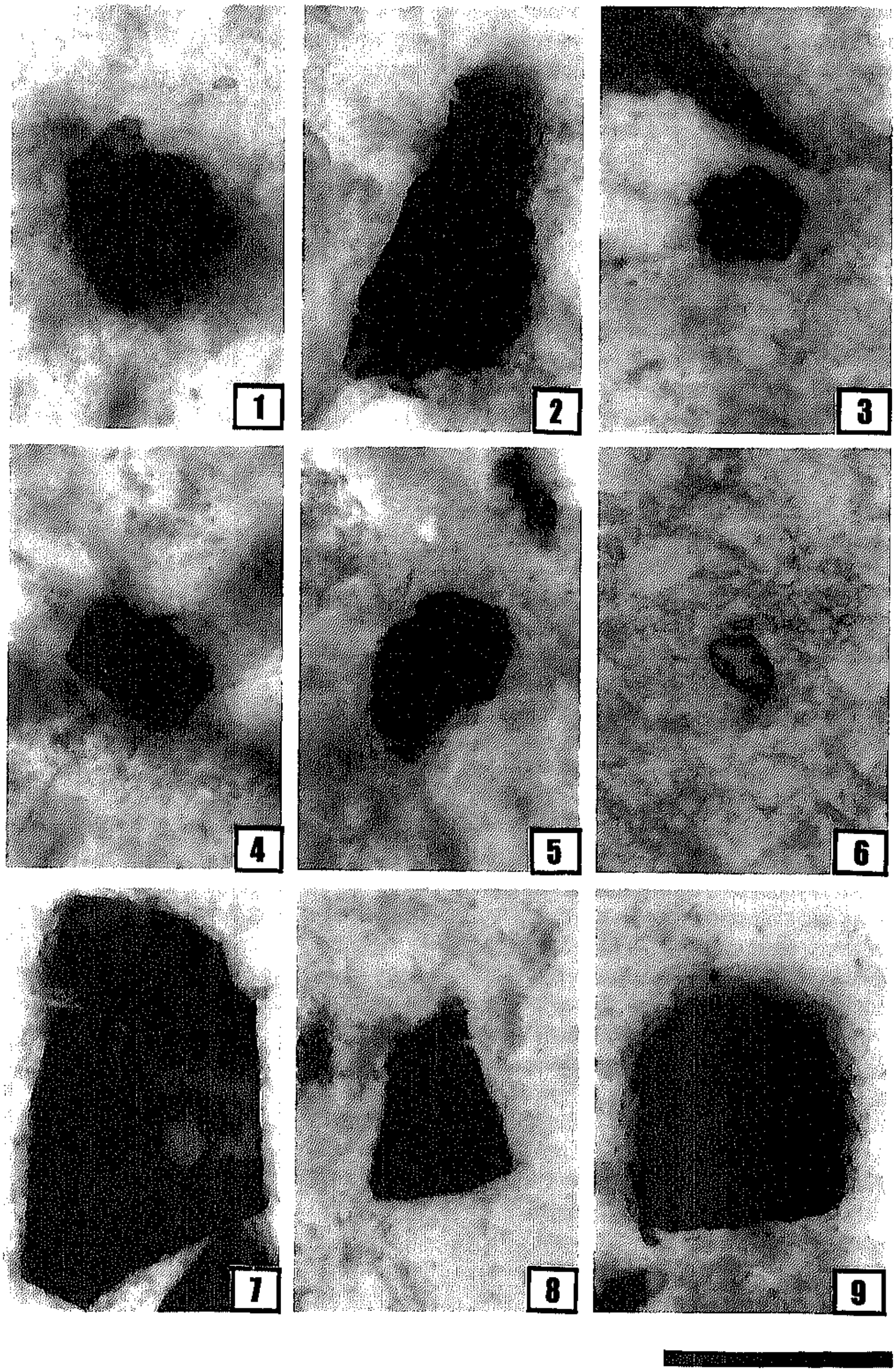
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Table 3. Representative microprobe analyses of detrital chromian spinels from the Hikoroichi Formation.

	C21	C25	C27	C32	C33
SiO_2	0.37	0.02	0.14	0.15	0.08
Al_2O_3	20.86	29.36	10.37	10.27	6.43
TiO_2	0.37	0.35	0.17	0.23	0.25
Cr_2O_3	40.29	32.48	55.14	51.40	60.04
FeO*	21.66	23.88	18.55	27.66	22.16
NiO	0.01	0.16	0.09	0	0.05
MnO	0.21	0.30	0.34	0.42	0.30
MgO	16.04	15.53	12.35	9.09	9.94
CaO	0.08	0.13	0.12	0.04	0.07
Na_2O	0.17	0.07	0	0.01	0.01
K_2O	0.05	0.02	0.04	0.01	0.02
Total	100.10	102.30	97.36	99.29	99.36
Mg#	0.73	0.67	0.62	0.46	0.50
Cr#	0.56	0.43	0.78	0.77	0.86
Cr3#	0.49	0.38	0.73	0.68	0.81
Al3#	0.37	0.50	0.20	0.20	0.13
Fe3#	0.14	0.12	0.07	0.12	0.06

FeO*: total iron as FeO. Mg#: Mg/(Mg+Fe^{2+}) atomic ratio. Cr#: Cr/(Cr+Al) atomic ratio. Cr3#:, Al3#: and Fe3#: atomic fraction of Cr, Al and Fe^{3+}, respectively, for trivalent cations (Cr + Al + Fe^{3+}). Ratios of Fe^{2+} and Fe^{3+} were calculated assuming spinel stoichiometry.

ways contain relatively low Cr_2O_3 content. These grains display paler colour than those containing high content of Cr_2O_3.

Most of the chromian spinel grains from the Hikoroichi Formation contain high percentages of Cr_2O_3, from 32.5 to 60.0%, with the average of 48.4% (Table 3). This may have caused reddish brown colour of the chromian spinels. Moreover, Al_2O_3 of these spinels are quite low due to the strong Cr^{3+}- substitution.

The Cr# (= Cr/(Cr+Al) atomic ratio) of spinels from the Nakazato Formation has a wide range from 0.39 to 0.83, though Mg# (= Mg/(Mg+Fe^{2+}) atomic ratio) has a rather narrow range from 0.42 to 0.68 (Fig.6). TiO_2 content is lower than 0.84 wt% (Fig.7), and almost of spinels are below 0.25 wt% in terms of TiO_2. Fe^{3+}/(Fe^{3+}+Cr+Al) atomic ratio is also generally low, <0.09 (Fig.8). The Cr# and Mg# of the Hikoroichi Formation have similarly a wide range, 0.43 to 0.86 and 0.37 to 0.73, respectively, and are similar to those of the Nakazato Formation (Fig.6). TiO_2 content is below 0.60 wt% (Fig.7) and Fe^{3+}/(Fe^{3+}+Cr+Al) atomic ratio is relatively high, but is lower than 0.14 (Fig.8).

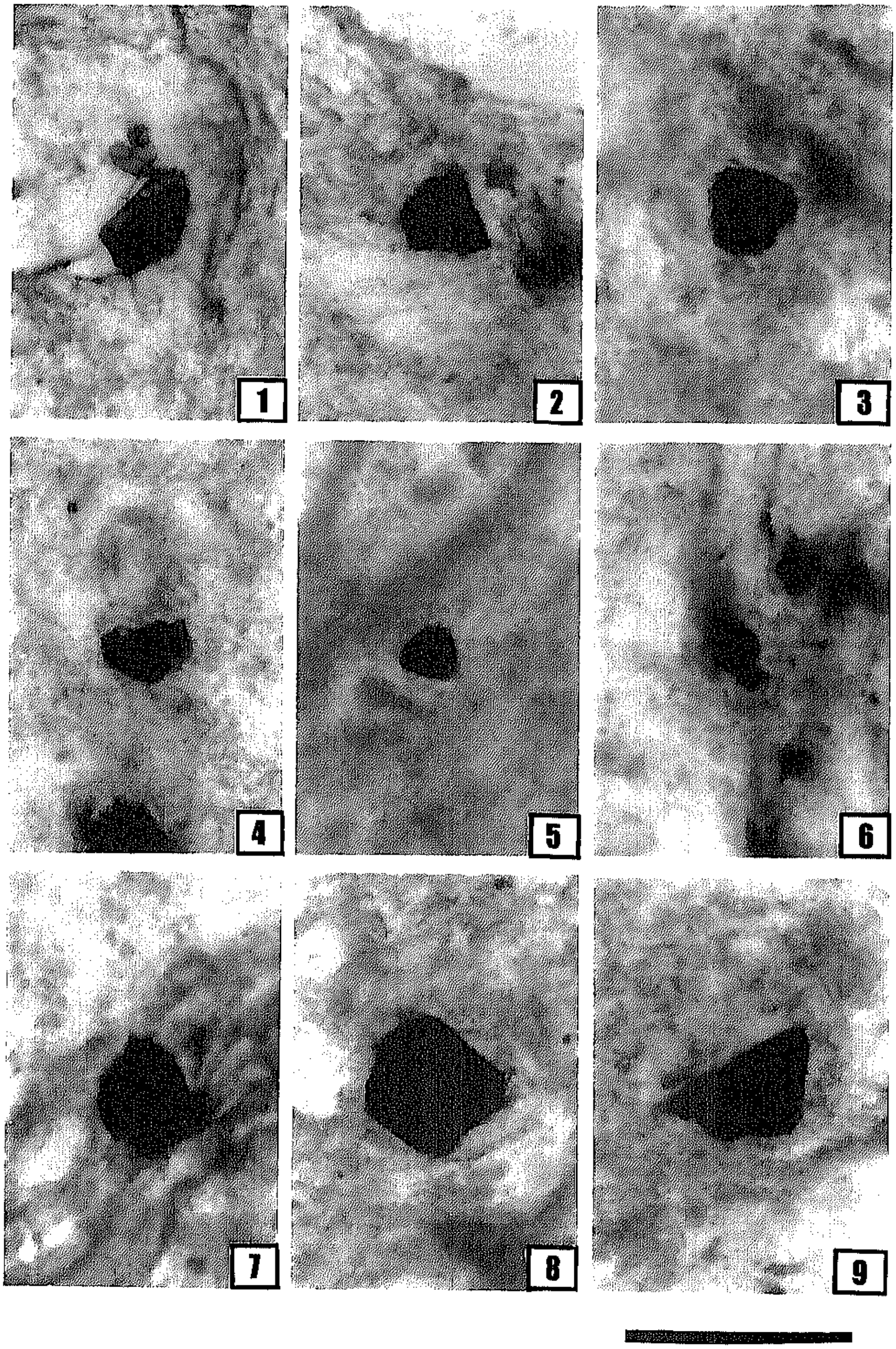
Comparison with other chromian spinels in SKT

Detrital chromian spinels from the Paleozoic of SKT in the Abukuma and Southern Kitakami Mountains were reported from several authors (Hisada *et al.*, 1995, 1997;Hisada and Arai, 1999;Yoshida *et al.*, 1995) (Fig. 9). Yoshida *et al.* (1995) reported the occurrence of detrital chromian spinels from the Silurian in the Ohasama area which belongs to the Hayachine tectonic belt. Most of detrital chromian spinels are characterized by a very low Fe^{3+}/(Fe^{3+}+Cr+Al) atomic ratio (below 0.1) (Fig. 9). TiO_2 content is generally low, <0.5, whereas Cr# is relatively high, 0.4-0.9. The negative correlationship between Mg# and Cr# is presented.

Hisada and his colleague discovered detrital chromian spinels from the Devonian to Carboniferous in three areas of SKT; Soma, Nagasaka and Kamaishi areas (Fig. 1). The followings are a brief description of the chemistry of the chromian spinels described by Hisada *et al.* (1995, 1997) and Hisada and Arai (1999). The relationships among Cr#, Mg#, and TiO_2 content, and Fe^{3+}-Cr-Al are shown in Figs. 9, 10 and 11.

Detrital chromian spinels from the Soma area in the Abukuma Mountains are characterized by a wide range of Cr#, from 0.2 to 0.8 as a whole. It is noteworthy that the detrital spinels in the pre-Upper Devonian Matsugadaira metamorphic rocks, and Upper Devonian Ainosawa and Lower Carboniferous Mano Formations share the same compositional trend, though they have

←Fig. 4. Photomicrographs of detrital chromian spinels from the Nakazato Formation in the Hikoroichi area. Scale bar: 100 μm. 1: D3, 2: D4, 3: D5, 4: D6, 5: D8, 6: D7, 7: D19, 8: D20, 9: D9.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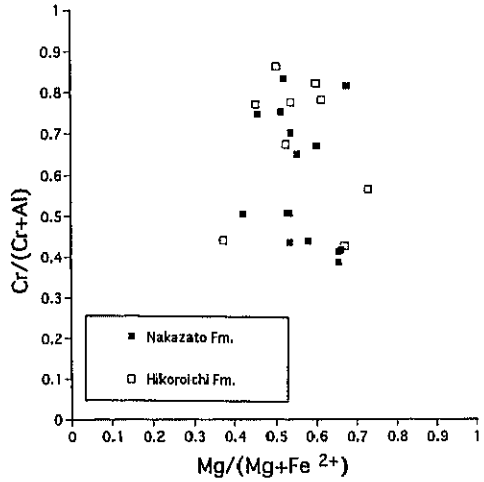

Fig. 6. Relationships between Mg/(Mg+Fe^{2+}) (=Mg#) and Cr/(Cr+Al)(=Cr#) of detrital chromian spinels from the Hikoroichi area.

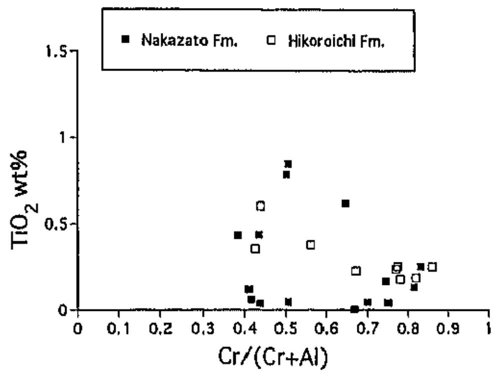

Fig. 7. Relationships between Cr/(Cr+Al)(=Cr#) and TiO_2 content of detrital chromian spinels from the Hikoroichi area.

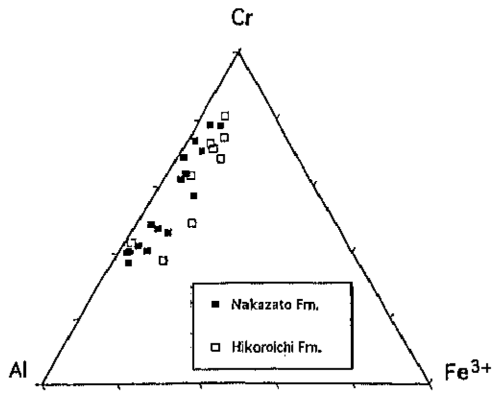

Fig. 8. Cr-Al-Fe^{3+} ratios of detrital chromian spinels from the Hikoroichi area.

different Cr# ranges. Spinels from the Ainosawa Formation are higher in Cr# than those from the Mano Formation. The compositional range for spinels in the Matsugadaira metamorphic rocks is almost equivalent to the whole chemical range for the other two formations. Both Fe^{3+}/(Fe^{3+}+Cr+Al) ratio and TiO_2 content are generally low, <0.08 and <0.16 wt%, respectively. Mg# has a negative correlationship with Cr#.

The Cr# atomic ratio of spinels from the Upper Devonian Tobigamori Formation in the Nagasaka area of the Southern Kitakami Mountains has a wide range, 0.17-0.82, though Cr#s are mostly plotted within a narrow range, 0.30-0.55. Mg# atomic ratio has also a wide range, 0.27-0.73, having a negative correlationship with the Cr#. Both TiO_2 content and Fe^{3+}/(Fe^{3+}+Cr+Al) atomic ratio are generally low, < 0.31 wt% and <0.10, respectively, except a few examples. The Cr# and Mg# of the Lower Carboniferous Karaumedate Formation have similarly a wide range, 0.24-0.76 and 0.26-0.72, respectively, and are very similar to those of the Tobigamori Formation. The negative relationship is also present between Cr# and Mg#. TiO_2 content is below 0.9 wt% and Fe^{3+}/(Fe^{3+}+Cr+Al) atomic ratio is relatively high, but is lower than 0.23.

Detrital chromian spinels from the Upper Devonian Senjyogataki Formation in the Kamaishi area of the Southern Kitakami Mountains have a similar trend to the others. The Cr# and Mg# are 0.35-0.92 and 0.18-0.75, respectively. Fe^{3+}/(Fe^{3+}+Cr+Al) atomic ratio and TiO_2 content are similarly and generally low, below 0.18 and 0.5 wt%, respectively. In terms of TiO_2 content, however, there may be two groups divided by 0.25 wt%. The negative

←Fig. 5. Photomicrographs of detrital chromian spinels from the Hikoroichi Formation.
Scale bar: 100 μm. 1: C21, 2: C22, 3: C25, 4: C27, 5: C28, 6: C33, 7: C30, 8: C31, 9: C32.

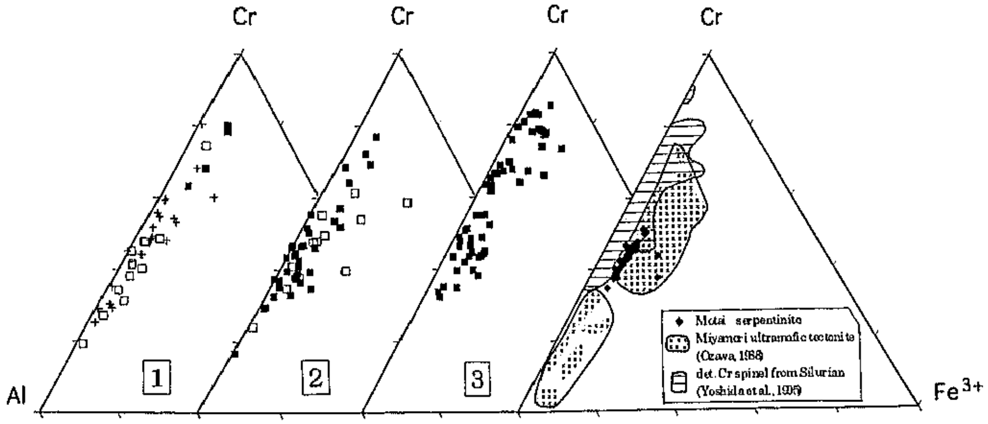

Fig. 9. Cr-Al-Fe^{3+} ratios of chromian spinels from the South Kitakami Terrane. 1-3: detrital chromian spinels from the Soma 1 (Hisada *et al.*, 1995), Nagasaka 2 (Hisada *et al.*, 1997) and Kamaishi 3 (Hisada and Arai, 1999) areas. In the Soma area 1, cross: Matsugadaira metamorphic rocks, closed square: Ainosawa Fm and open square: Mano Fm. In the Nagasaka area 2, closed square:Tobigamori Fm and open square: Karaumedate Fm. In the Kamaishi area 3, closed square: Senjyogataki Fm.

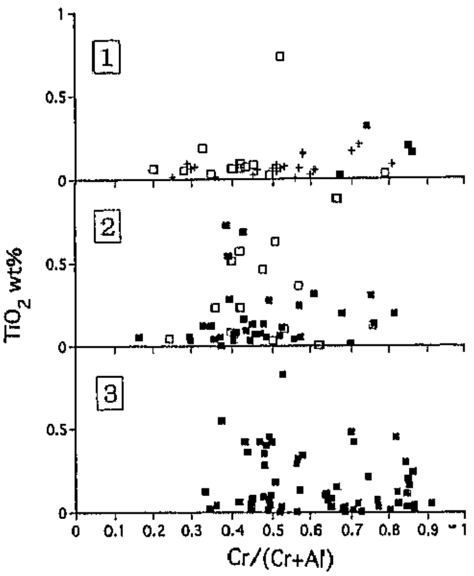

Fig. 10. Relationships between Cr/(Cr+Al)(= Cr#) and TiO_2 content of detrital chromian spinels from the South Kitakami Terrane. 1-3: detrital chromian spinels from the Soma 1 (Hisada *et al.*, 1995), Nagasaka 2 (Hisada *et al.*, 1997) and Kamaishi 3 (Hisada and Arai, 1999) areas. In the Soma area 1, cross: Matsugadaira metamorphic rocks, closed square: Ainosawa Fm and open square: Mano Fm. In the Nagasaka area 2, closed square: Tobigamori Fm and open square: Karaumedate Fm. In the Kamaishi area 3, closed square: Senjyogataki Fm.

relationship is also present between Cr# and Mg#.

On these comparison, detrital chromian spinels from Devonian to Carboniferous in SKT including the Hikoroichi area are characterized by the similar chemistries; very low $Fe^{3+}/(Fe^{3+}+Cr+Al)$ atomic ratio and TiO_2 content, and a wide range (0.4-0.9) of Cr# and Mg#.

The Miyamori ophiolitic complex (= Miyamori ultramafic complex in Fig.1), consists of ultramafic tectonite and cumulate members with intrusions of gabbroic and other rocks (Ozawa, 1988). Ozawa (1988) presented detailed petrological data of the ultramafic rocks of the Miyamori ophiolitic complex. Chromian spinels in the Miyamori ultramafic tectonites (recrystallized ultramafic rocks) have low $Fe^{3+}/(Fe^{3+}+Cr+Al)$ ratios and a wide range of the Cr#, from 0.1 to 0.8. (Fig. 9)

Tectonic setting inferred from detrital chromian spinels

According to the discrimination diagram proposed by Dickinson *et al.* (1983), the sandstones of the Nakazato and Hikoroichi Formations fall in the magmatic arc provenance field. The quite high proportion of volcanic lithic and plagioclase grains, and the corresponding relatively

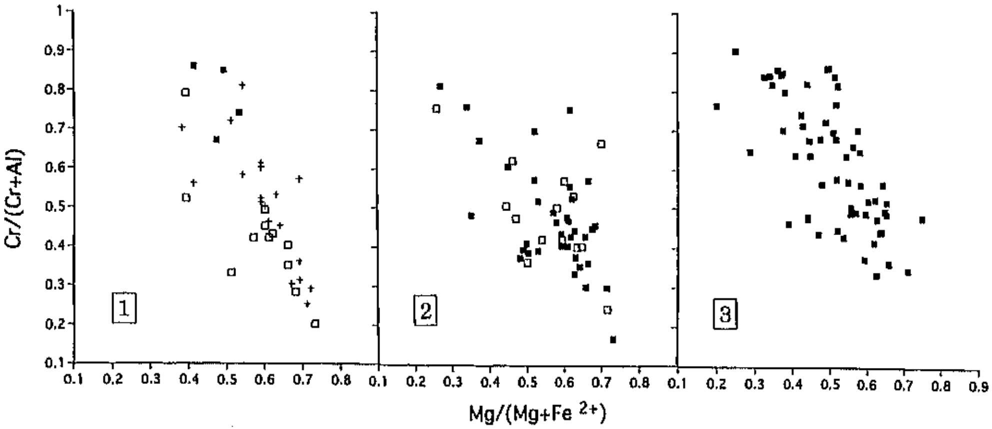

Fig. 11. Relationships between Mg/(Mg+Fe^{2+}) (= Mg#) and Cr/(Cr+Al)(=Cr#) of detrital chromian spinels from the South Kitakami Terrane. [1]-[3]: detrital chromian spinels from the Soma [1] (Hisada *et al.*, 1995), Nagasaka [2] (Hisada *et al.*, 1997) and Kamaishi [3] (Hisada and Arai, 1999) areas. In the Soma area [1], cross: Matsugadaira metamorphic rocks, closed square: Ainosawa Fm and open square: Mano Fm. In the Nagasaka area [2], closed square: Tobigamori Fm and open square: Karaumedate Fm. In the Kamaishi area [3], closed square: Senjyogataki Fm.

low proportion of quartz and K-feldspar, suggest that the main detritus were derived mainly from volcanic island arc as opposed to the continental arc. The high amount of lithic clasts relative to feldspar and quartz, is a characteristic of undissected volcanic arc. Mikami (1971) concluded that clastics for the Devonian and Lower Carboniferous sandstones were provided mainly from intermediate and mafic volcanic rocks and subordinately from intermediate and mafic hypabyssal and plutonic rocks. Therefore the undissected, partly dissected, volcanic arc is inferred as a provenance from these conclusions. Considering the detrital chromian spinels, parts of Devonian to Carboniferous clastics in SKT can be regarded to have been mainly derived from mafic-ultramafic terranes. In addition, as pointed out by Kawamura, T. (1984) and Okami *et al.* (1994), the clastics of the Hikoroichi Formation seem to have been deposited around volcanic islands at distances from the continent.

The chemistry of chromian spinels is useful for discriminating host rocks of ultramafic and mafic rocks as mentioned above. Namely based upon the rather wide range of Cr# and relatively low TiO_2 and Fe^{3+}/(Cr+Al+Fe^{3+}) atomic ratio of the studied chromian spinels, it is suggestive of their derivation from residual peridotites of the upper mantle origin (cf., Arai, 1994). The relatively higher proportion of high Cr# (0.85) spinels in the Devonian to Carboniferous clastics, especially, advocates a fore-arc origin for the source peridotite suite. The appearance of these detrital chromian spinels strongly suggests that SKT during Middle Devonian to Early Carboniferous were deposited in the fore-arc tectonic environment. Quite similar tectonic setting was also recognized for the Upper Devonian clastics in the Kurosegawa terrane, SW Japan (Hisada and Arai, 1999) as well as the Silurian clastics in SKT (Yoshida *et al.*, 1995).

Ozawa (1988) divided the ultramafic tectonite suite of the Miyamori ophiolitic complex into aluminous spinel-bearing peridotites and pyroxenites, and chromian spinel-bearing peridotites and pyroxenites by the gap of Cr# of spinels, from 0.35 to 0.40. He pointed out that the latter was formed beneath an island arc and the former was formed beneath a back-arc basin. The wide range for Cr# of the detrital chromian spinels from SKT is basically similar to the spinels from the Miyamori ultramafic tectonites (Fig. 9). This gap of Cr# can not be recognized in the detrital chromian spinels from SKT, in which the spinels with intermediate Cr#, from

0.3 to 0.6, are conspicuous. This may indicate that the exactly same rocks as the present Miyamori ophiolite can not be the source for the detrital spinels of SKT.

As speculated by Saito and Hashimoto (1982) on the basis of paleontologic and paleomagnetic results, SKT has been a fragment of a lost continent situated near Gondwanaland during Middle Paleozoic age. Recently Ehiro and Kanisawa (1999) supposed that the South Kitakami Microcontinent was developed as an accretionary prism during Cambrian-Ordovician, which was a southward extension of the South China Accretionary Fold Belt located near Indochina. Also they insisted that this idea is advocated by the fact that Silurian coral faunas found in SKT are quite similar to those of Australian and South China affinity (Kato, 1990). Hisada and Arai (1999) concluded that not only SKT but also the Kurosegawa terrane were located in the northern peri-Gondwanaland during Devonian, and both were deposited in the fore-arc region associated with trench where the Paleo-Pacific plate was consumed. This conclusion was deduced from the occurrence and chemistry of detrital chromian spinels from the Upper Devonian, i.e. plant fossil *Leptophloeum* -bearing beds, in the Kurosegawa terrane. The paleogeography of this arc is unsolved yet, however, their depositional sites seem to have been situated near South China or Indochina during Late Paleozoic.

Conclusions

1. Detrital chromian spinels were discovered in sandstones and siltstones of the Middle Devonian Nakazato Formation and Lower Carboniferous Hikoroichi Formation in the Hikoroichi area.

2. Petrographic and geochemical investigations suggest that the detrital chromian spinels from the Hikoroichi area were provided from ultramafic rocks, which is related to the fore-arc setting.

3. The studied SKT detrital chromian spinels indicate peridotite source rocks occurred in the island-arc tectonic region of the northern peri-Gondwanaland.

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